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STUDY AND COMPARISON OF THE PROPOSED METHODS OF FORCE COOLING OF POLYETHYLEN PIPES (PE PIPES)

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ABSTRACT

The current study provides several cooling methods for rapid electrofusion welding, all of which have more optimal cooling compared to natural cooling. However, the criteria for selection of a proper fluid is, along with reduced cooling time and operability, is optimization of the process, improved quality of the final weld and minimizing the decrease in weld strength. Analyses on the fluid samples use for rapid cooling show that it is suitable for cooling to start after the end of crystallization step, or to first move past the crystallization step using air or dry ice and with a suitable rate, before starting rapid cooling to room temperature using a fluid such as water after the end of crystallization. The results obtained from rapi cooling under different conditions show the advantages of using water and air as a suitable fluid. Using air in the temperature range of 10 to 30°C and water in the temperature range of 23 to 30°C result in minimum change in physical properties comparted to natural cooling. Furthermore, using water as the fluid is more suitable than air when it comes to cooling time, with air resulting in less decrease in cooling time while also minimizing changes in physical properties compared to reference values.

INTRODUCTION

Polyethylene pipes were used for the first time in 1950s in water and gas supply projects in United States [1, 2]. During electrofusion welding of polyethylene pipes, cooling phase is a critical step for achieving suitable strength. During this phase, polymer chains which has been diffused across the cross-section area must be locked in place by all or part of the polymer chains participating in the crystalline surface around the coupling. Formation of these bridges and their bonding around the pipe will then result in suitable ductility and strength of the weld [3].

Since polyethylene's strength is greatly affected by temperature, decreasing the temperature at the coupling's center to room temperature

results in increased strength of the connection. Therefore, at ambient temperature, electrofusion welds undergo ductile fractures during adhesion or tensile strength tests. The reason for this response is the presence of molecules which have diffused through the cross-section, forming bonds and connections with both sides of the coupling [4].

One study, prepared three similar polyethylene films and selected heating conditions so that three samples with different crystallizations were obtained. As predicted, the percentage of crystallinity was inversely proportional to the cooling speed. This meant that at lower polymer cooling rates, polymer chains had more time for gathering around the cores, resulting in increased volume strength of the samples but decrease in their fracture voltage [5].

Studies show that electrofusion connections can result in changes in the connected pipes. For example, increase in the internal diameter of the pipe after fusion can lead to the resin filling the created empty space, changing the physical properties of the pipe. In polyethylene pipes cooled using external methods, the outside layer will have lower density and crystallinity and the thermal energy input during electrofusion decreases with cooling rate [6].

Polyethylene pipes are used for transfer of petroleum products as well as in cooling applications in nuclear reactors due to their special resistance against corrosion and abrasion and fusion and electrofusion welding are among the most common approaches for connecting these pipes [7]. In the electrofusion welding, the quality, tensile properties, load tolerance, resistance and other properties of the resulting weld are better compared to fusion welding [8].

In one study [9], infrared waves were used to evaluate cracks in the welding area of polyethylene pipes. This study used IR non-destructive test on polyethylene pipes in order to evaluate the welding area and presence of cracks. Brittle fractures were observed in tensile strength samples of electrofusion welding for polyethylene pipes with low welding time due to crack initiation and growth in the welding cross-section [4, 10, 11].

Rajabi et.al. [12], provided a simulation of electrofusion weld using Boltzmann network and used D2Q9 and D2Q5 network models for determining density and temperature. Their results indicated that heat transfer rate based on Nusselt number effectively changed with distance, height and size of electrical wires inside electrofusion joints. They also reported that increase in the relative distance and size of the wires will result in increased melting rate. These results provided a good estimation for selection of design parameters for electrofusion joints.

In a study by Starostin et.al., the thermal process of welding in polyethylene gas pipes was investigated at various temperatures under standard temperature. In these tests, the technical weld parameters were evaluated and the results were used to determine electrofusion welding parameters for polyethylene gas pipes. The effect of ambient temperature and temperature changes on polyethylene saddle coupler sample was also investigated [13].

Bowman [14] showed that the quality of connections is low for small gaps. Increase in the gap size until around 2% increases the strength of the coupling but larger gaps also decrease the welding strength. In a study by

Nishimura et.al. [4], no significant differences were observed in the formed connection for gap sizes between 0 to 0.25mm while gap sizes larger than 0.5mm failed to form a suitable connection.

In their study, Higuchi et.al. investigated suitable cooling retimes for electrofusion welding of polyethylene pipes used for transportation of gas fuels Their observations included factors such as deformation of the molten zone, crystallization percentage, molecular orientation, creep strength and tensile fatigue for long-term use of polymer pipes [15]. Navidfamili et.al. investigated the factors affecting the electrofusion welding of polyethylene pipes. Formation of current bonds in this type of welding and resistance against crack initiation and growth was among problems investigated in their study [16]. Investigation of the environmental factors on the strength of electrofusion welding of polyethylene pipes was carried out by Abolabasi and the results showed that welding at high temperatures increases the possibility of welds with low mechanical strength at polymer cross-section but this does not mean a welding with unsuitable strength [17].

According to the estimations and need assessment carried out by Gas Company of Isfahan Province, cooling process after electrofusion welding requires a long time and results in lack of feasibility from time and cost perspectives. Therefore, it is necessary to decrease this cooling time. According to IGS standards, around one hour must pass after electrofusion welding, depending on the type of coupling, before the welding can be evaluated using various tests. During the initial investigations, it was revealed that the reason for the long cooling time, it the use of natural convection for cooling. Therefore, it is possible to use forced convection process with a suitable fluid to significantly decrease this cooling time. The criterion for achieving suitable results is the data obtained from crush test according to IGS standards.

The welding of thermoplastic pipes is important due to their work conditions and resistance against chemical compounds. Electrofusion welding is one of the methods used for connecting these pipes under most conditions. In the electrofusion welding process, the energy required for joining the pipe and the coupler is provided through alternating sinus electrical current (usually 39.5 volts) through a thermal resistant ring. In order to control the energy transfer to the coupler, the current is usually connected for a set duration (welding time) which is usually provided in a chart by the manufacturer of the pipes. The results of a study on modeling of thermal conductivity and estimation of thermal welding parameters in electrofusion couplers of gas pipelines indicated that proper temperature range explains 84.04% of variance in weld quality [18].

Based on the operational and implementation limitations, water, soil and air were selected as possible fluids due to their abundance at any location. On the other hand, some studies [19, 20] have suggested the use of ice and dry ice. To this end, these two methods were also investigated in order to compare the results despite their lower accessibility. After simulation for each fluid, the time require for reaching predefined temperatures was determined and necessary estimations for that fluid were used for experimental investigations.

Since the evaluation of welds has always been one of the required processes, various destructive and non-destructive methods have been

proposed for evaluating the quality of the welding. In recent studies, a Chinese team developed two methods for non-destructive evaluation of welding based on ultrasound technology for detection of defects. However, this method has high cost and low-quality results. Therefore, the use of destructive tests such as crush test is often preferred [21].

According to the field studies and literature review, it can be said that the most important factor in formation of suitable electrofusion connections, is proper cooling method. Furthermore, the basis of a suitable cooling is suitable heat distribution and control of temperature gradient at the inside and outside of the coupling. Proper analysis of heat conductivity can help achieve a suitable cooling with a shorter duration.

GOVERNING EQUATIONS

If heat transfer is simultaneous with movement of fluid, then the heat is transferred through convection. This process includes the induced movement of fluids during phase change such as raising of bubbles during boiling or decent of water droplets during condensation as well as fluid movements during melting and freezing. In the current study, the freezing process is investigated which results in a phase change in the material.

Phase Change Materials (PCM) are materials used for storing the latent heat and change their phase with increase or decrease in thermal energy [22]. These materials can absorb or release latent fusion heat and change their phase from liquid to gas or vise versa by absorbing or releasing latent evaporation heat. They can also absorb or release latent sublimation heat in order to change their phase from solid to gas or vise versa [23]. In the graph showing the phase change from solid to liquid, the shaded areas show the heat energy absorbed or released during the phase change process. Total stored energy includes the energy used for heating the solid, the latent phase change heat at constant temperature and the heat used for increasing the temperature of the liquid.

In Fluent simulations, after numerical modeling and simulation of melting process with constant heat flux conditions (current analysis) it can be predicted that melting rate increases over time and this increase is larger in the initial part of the melting and decreases in the middle and end of the melting process. Furthermore, during the initial stages of the melting, the heat transfer is mostly through conduction while convection will become the dominant mechanism at later stages [24]. In a study of energy absorption system of phase change materials, the results indicated that in PCMs, temperature increase gradient is large until melting point after which the temperature increases with a slow gradient [25].

Another study used mathematical simulation of PCMs using Fluent software and Enthalpy – porosity approach for modeling of melting and freezing processes. In this approach, the interface between solid and liquid phases is not determined and instead a value called liquid volume fraction is used which is the fraction of the cell volume at liquid phase with its value calculated using enthalpy for each iteration. The mushy zone is the zone with a liquid volume fraction between 0 and 1 and is modeled similar to a porous media in which the porosity changes from 1 to 0 during freezing. When the material inside the cell is fully frozen, the porosity is zero. Fluent software

can use two possible solution methods of pressure-based and density-based, with the only possible approach for solving freezing and melting processes being pressure-based approach [26].

Another study used HDPE (910 Kg/m3) as the phase change material for energy optimization in water heaters and carried out numerical and empirical analyses. The results indicated that polyethylene used as PCM in water reservoir can help control and retrain the water temperature for a longer duration which is due to low thermal conductivity of polyethylene. This study provided some suggestions for implementation of this method using polyethylene balls or other PCM samples [27].

These studies indicated that polyethylene will have a dual-phase behavior similar to PCMs during welding and cooling cycles. During this process, the interface between phases moves constantly and the transitional properties significantly change between different phases due to differences between energy, mass and momentum transfer rates between phases. In these problems, the position of the interface can't be determined but should be considered as an important factor during the solution [28].

In the phase change problems, the governing equations for enthalpy – porosity method are as follows [29]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = o \tag{1}$$

In which ρ is the density and U being the velocity of the fluid.

Heat transfer equation:

The heat equation is a linear partial differential equation which describes the distribution of heat (or changes in temperature) in its domain. Electrofusion welding includes two main steps:

Heating step, during which the energy is applied through welding equipment;

Cooling step; during which the coupler is allowed to cool;

Heat equation for electrofusion process is as follows:

$$\rho(t) \cdot C_p(t) \cdot \frac{dT}{dt} = \frac{dT}{dt}\left(k(T)\frac{dT}{dt}\right) + H \tag{2}$$

In which ρ is the density, k is thermal conductivity and H is the power in units of volume for crystallization or fusion and can be a function of crystallization enthalpy in units of volume. For a pure crystal, we have

$$\Delta H_c^{100\%} = 290 \frac{J}{g}:$$
$$H = \rho \Delta H \frac{dX_c}{dt} \tag{3}$$

In which H is the crystallization enthalpy and Xc is the crystallization fraction.

$$\Delta H = \Delta H_c^{100\%} X_c \tag{4}$$

By placing equations 3 and 4 in equation 3-4, we have:

$$\frac{dT}{dt}\left(k(T)\frac{dT}{dt}\right) \qquad \rho \cdot \left(C_p \cdot \frac{dT}{dt} - \Delta H_c^{100\%} X_c \frac{dX_c}{dt}\right) = \tag{5}$$

By separating the dT/dt term from both sides of equation 5, we have:

$$\frac{dT}{dt}\left(k(T)\frac{dT}{dt}\right) \qquad \rho \cdot \left(C_p - \Delta H_c^{100\%} X_c \frac{dX_c}{dt}\right)\frac{dT}{dt} = \tag{6}$$

By defining Cpm as modified heat capacity (equation 7), equation 6 can be transformed to equation 8:

$$C_{pm} = C_p - \Delta H_c^{100\%} X_c \frac{dX_c}{dt} \tag{7}$$

$$\frac{dT}{dt}\left(k(T)\frac{dT}{dt}\right) \; \rho \cdot \left(C_{pm}\right)\frac{dT}{dt} = \tag{8}$$

Cpm can be used to calculate the modified heating capacity based on temperature for each cooling rate. Since polyethylene has low head conductivity coefficient, the slope of temperature changes is expected to be high.

STUDY METHOD

In the current study, first, the cooling process for a coupling during electrofusion welding was simulated under natural conditions with temperature values and criteria specified by the Technical Inspection unit of Isfahan Gas company and changes in temperature and time in a number of locations were determined and cooling was carried out according to the current IGS standards. Then, in another simulation, rapid cooling was carried out after the end of crystallization. The results of this stage determine the amount of saved time due to rapid cooling after formation of crystals.

After the end of crystallization stage, rapid cooling can be used to rapidly decrease the temperature gradient inside the pipe and on the surface of the coupling without any changes in the crystallization process compared to natural cooling method; resulting in faster electrofusion welding compared to natural method with 47% less time required for the welding process. Under natural conditions, electrofusion welding of a 110mm coupling requires 180 seconds of heating, 600 seconds of initial cooling and approximately 8400 seconds of final cooling for a total of 9180 seconds (approximately 150 minutes). However, this time can decrease to 80 minutes using rapid cooling approach. In this approach initial cooling time of 250 seconds and final cooling time of 600 seconds are used and thermal changes in the electrofusion cross-section and reference pipe were investigated.

The validation is carried out using different methods in different projects. Usually, the results of numerical analyses are compared to empirical

tests carried out by other researchers in order to determine the validity of the results.

The numerical method used in this study was carried out using test results and simulation results were evaluated using the results presented by Akio Nakashiba et.al. [30]. Geometry and type of the coupler used for the current study were selected based on the validation study.

Simulation was carried out for a 50mm coupler and nickel-copper wires with density of 9800 Kg/m3, heat capacity of 393.49 J/Kg.K and thermal conductivity of 232.56 J/m.s.K, at voltage of 74 volte. Similar to the validation research, the fusion duration was 110 seconds, initial cooling using phase change materials was 250 seconds and final cooling was 600 seconds. The results of this validation are presented in figure (1).
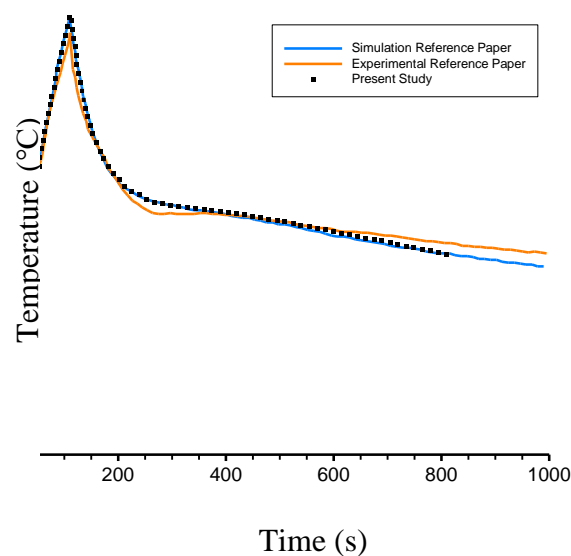
Figure (1): Comparison between the results of the current study and the results presented by Akio Nakashiba et.al. [30]

Table (1) shows the deviation and error percentages of the current results compared to the results presented by Akio Nakashiba et.al. [30]. To this end, at each time, the temperature values for each of the three graphs in figure (1) are determined and used to calculate error values. The largest error for the current simulation is 1.74% at the time of 650s.

Table 1: Comparison of error percentages at different times for simulation results

	t = 90s	t = 110s	t = 270s	t = 360s	t = 500s	t = 650s	t = 800s
Error percent compared to the simulation results of validation reference	0.49%	0.1%	0.12%	0.65%	1.11%	1.74%	0.23%

Error percent compared to the empirical results of validation reference	4.39%	4.9%	4.97%	1.91%	0.57%	1.37%	4.28%

In the next section, regardless of the change in crystallization process and final properties of the welding, rapid cooling using 4 proposed fluids are investigated and the best fluid is selected based on the operational factors, accessibility, feasibility and suitable cooling rate.

To this end, four different fluids including water and ice mixture, dry ice, water and air were selected. In order to compare and evaluate the changes and decrease in total welding process time, the simulation was repeated twice for each fluid.

- First simulation included cooling from outside of the coupling after an initial cooling time (600 s)
- Second simulation included cooling from outside of the coupling immediately after heating time (180s heating time).

Since one of the important factors for selection of suitable cooling fluid was its operability and it is not possible to flow dry ice or ice & water mixture through the pipes, cooling was carried out only from the outside.

It was assumed that the total time required for a full electrofusion welding cycle is around 2300 to 2500 seconds, after which the pipes are under stable conditions. When cooling under free convection, molten polymer volume at the center of the welding area reaches zero at around 2060 seconds, after which only heat transfer rate decreases over time. It is natural for this duration to decrease when using forced convection while the cooling rate will not be significantly affected after this time. Therefore, during simulations, no extra time was assigned to the welding process and the conclusions were obtained based on the data form the first 2500 seconds.

FINDINGS
Water & Ice Mixture

In this section, two different cooling methods using water and ice mixture were investigated.

In the first method, the fluid is considered to have water's properties at 1°C with the velocity of 0.1m/s, with the natural convection inside the pipe with coefficient of 6.4 W/m2K. In this method, the cooling is carried out at two different rimes, first 780 seconds after the start of the process and once 180 seconds after the start of the process. Figures (2), (3) and (4) show conditions where forced convection cooling is carried out after the initial cooling phase under natural convection (780 seconds after the start of the electrofusion process). On the other hand, figures (5), (6) and (7) show conditions where forced convection cooling has started immediately after the end of heating phase (180 seconds after the end of electrofusion process).

In the second method, water's properties at 1°C is determined by assuming that the pipe is cooled by being submerged in an ice water bath. In

this case, the water is stationary and has natural convection in which the heat transfer coefficient for natural convection is calculated using equations (3) and (6). This simulation is carried out based on the conditions of the experiments carried out in laboratory settings. Figures (8) to (12) show the data related to this simulation. Furthermore, this electrofusion sample was investigated using crush test which will be explained in the following sections.
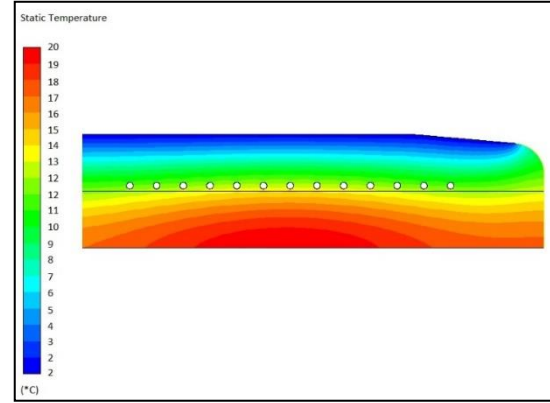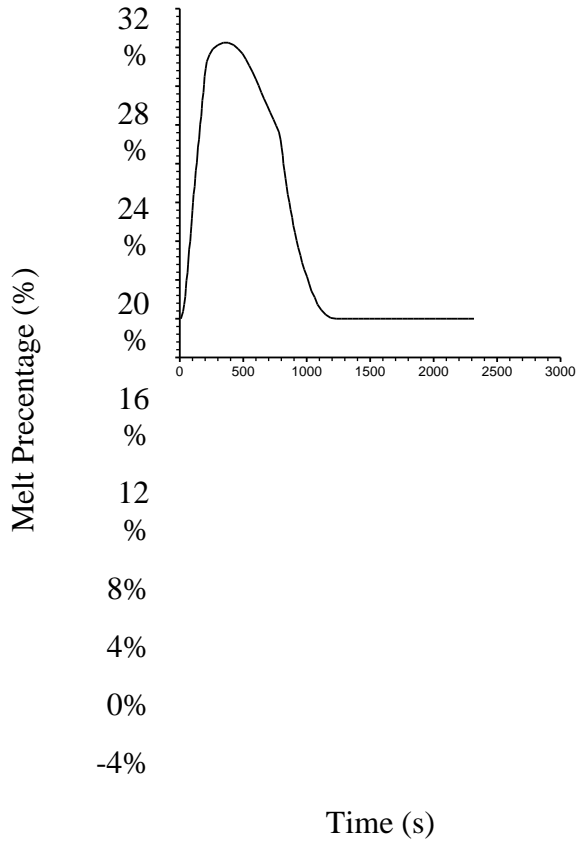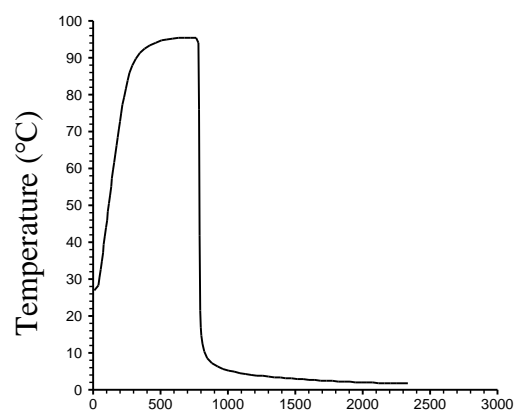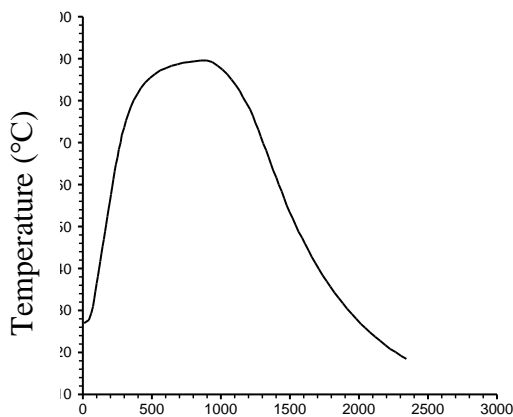

Figure 3: Changes in the molten polymer percentage after cooling with water and ice 780 seconds after the start of the electrofusion

Figure 2: Temperature counter after cooling with water and ice mixture 780 seconds after the start of the electrofusion

Time (s)

b) variations of internal surface temperature over time;

Time (s)

a) variations of external surface temperate over time;

Time (s)

d) variations in the fusion temperature over time

Time (s)

c) variations in temperature of heating wires over time;
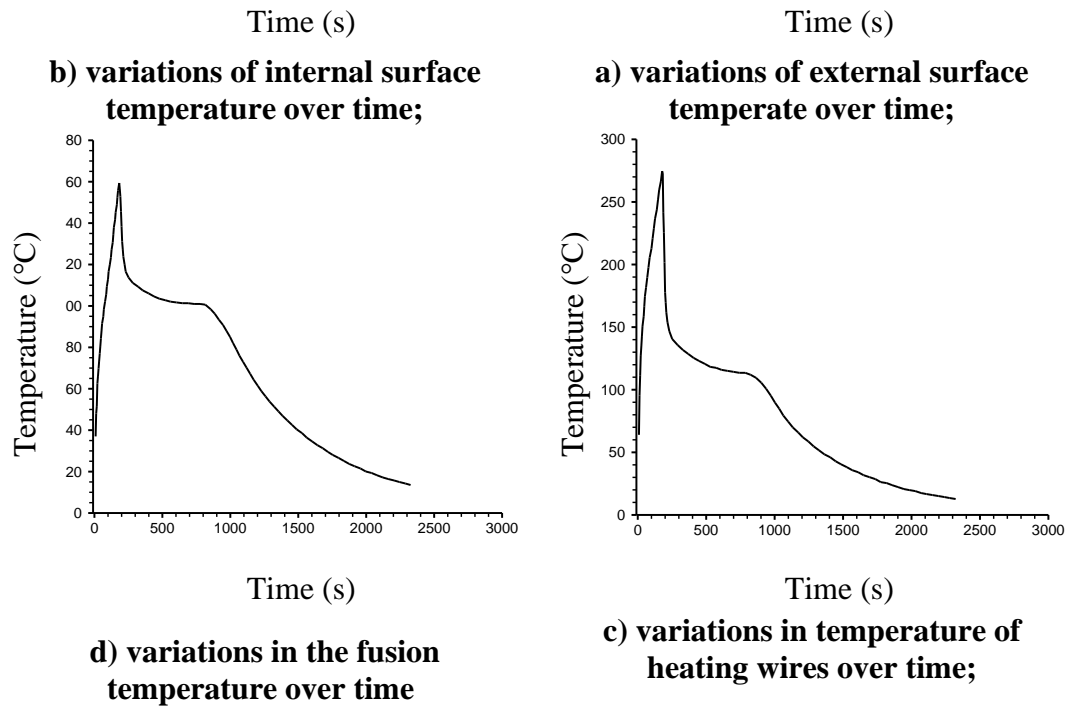
Figure 4: Changes in temperature over time for cooling with water and ice 780 seconds after the start of the electrofusion
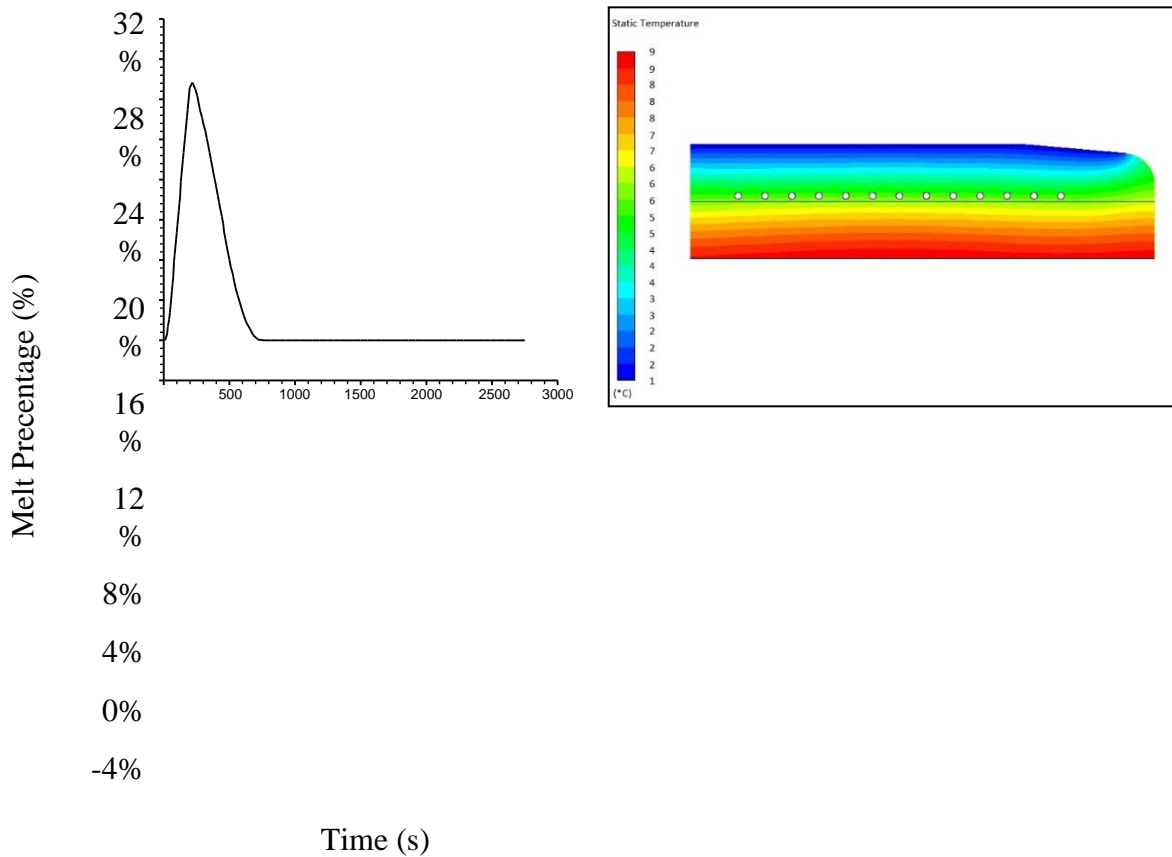
Figure 6: Changes in the molten polymer percentage after cooling with water and ice 180 seconds after the start of the electrofusion
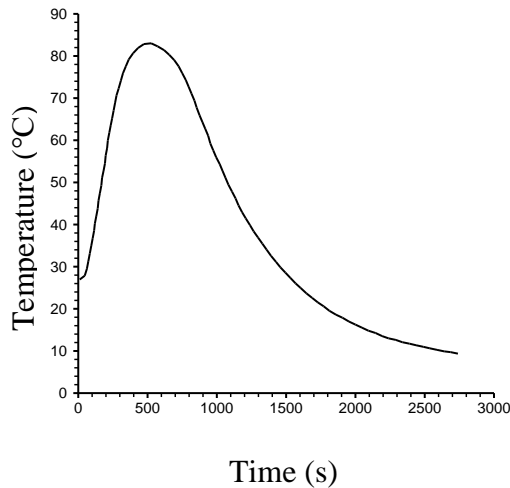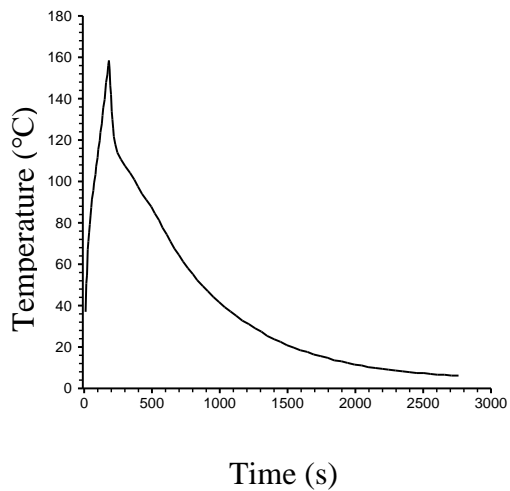
Figure 5: Temperature counter after cooling with water and ice mixture 180 seconds after the start of the electrofusion
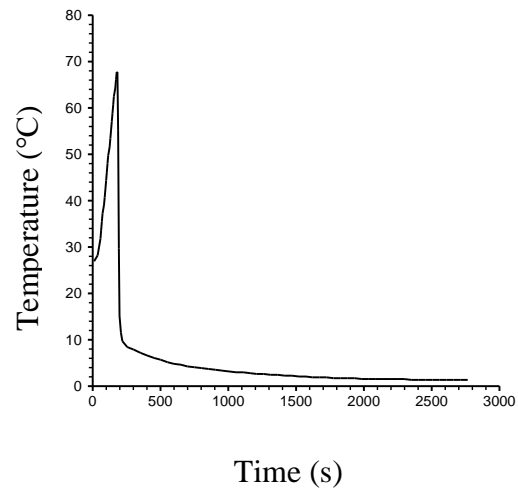
b) variations of internal surface temperature over time;

a) variations of external surface temperate over time;

d) variations in the fusion temperature over time;
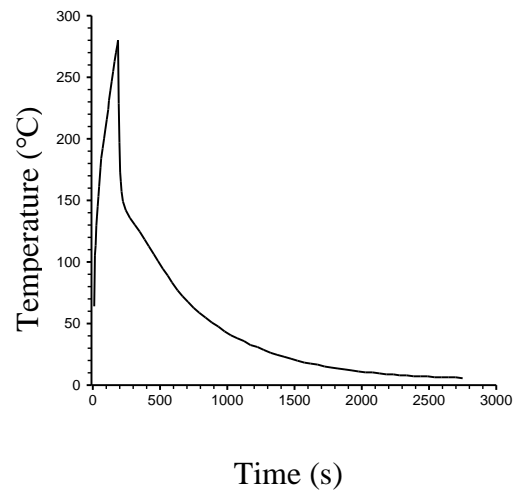
c) variations in temperature of heating wires over time;

Figure 7: Changes in temperature over time for cooling with water and ice 180 seconds after the start of the electrofusion

The result of rapid cooling with water and ice mixture using the abovementioned two methods show that in the first method, molten polymer volume has reached zero 1300 seconds after the start of the process, but this time is equal to 850 seconds for the second method. However, at this point, there is still a temperature gradient in the pipes and coupling and since rapid

cooling is applied from the outside of the pipe, the internal surface of the pipe has a higher temperature.

Furthermore, it can be concluded that since in the second method, rapid cooling has started immediately after the end of heating, formed crystals are smaller and there is a decrease in degree of crystallinity compared to natural convection conditions. However, in this method, crystals have a more uniform size distribution compared to the first method. In the first method, crystals which have cooled at a lower rate are larger compared to crystals formed in the later stages which are cooled rapidly, therefore resulting in less resistance against crack initiation. Furthermore, second method also requires less time. According to previous literature, the size of crystals is affected by the cooling rate of the polymer [31]. In order to investigate the effect of this cooling method on welding quality, a portable pipe and coupling (length of around 50 cm) underwent electrofusion under experimental conditions and the welding cycle was continued until the end of initial cooling period using natural convection.

Then, the clamps were opened and the pipe – coupling was submerged in an ice water bath. The sample was then investigated using crash test after 10 minutes. Figure (8) shows the completion of electrofusion process before submersion in ice water bath while figure (9) shows the submersion of the welded coupling in the ice water bath.

Figure 8: Welded coupling after initial cooling period before submersion in ice water bath;

b) stabilization of the coupling in the ice water bath   **a) placing the coupling in the ice water bath;**

Figure 9: Submersion of welded coupling in the ice water bath for 600 seconds

After the passage of the necessary time after submersion of pipe and coupling in ice and water mixture, four samples were prepared from the coupling for use in crush test as shown in figure 10.

Figure 10: Cutting of the coupling after final cooling for crush test

In this test, after cutting the coupling into four parts, compression force with the rate of 100 mm/min is applied to each sample and weld quality is evaluate based on the type of fracture surface as shown in figure 10.

| b) application of compression force to the second part of the sample coupling | a) application of compression force to the first part of a coupling |

Figure 11: Application of constant compression force during crush test

If no fracture exists or if the fracture occurs in the pipe, the sample has suitable welding quality. However, in case of fracture, welding quality is determined by evaluating the type of facture (brittle or ductile) (figure 12). After combining the results for all parts, the overall quality of the welding is determined.

According to the relevant standards (ISO 13955), is the fractured percentage of the length in the welding is less than 20%, then the welding is acceptable. According to equation (9) we have:

$$C_c = \frac{d_2}{y} \times 100 \tag{9}$$

In this equation, CC is the percentage of the surface with brittle fracture, d2 is the length of brittle fraction and y is the total length of the welding.

pipe rapture   **ductile fracture**   **brittle fracture**
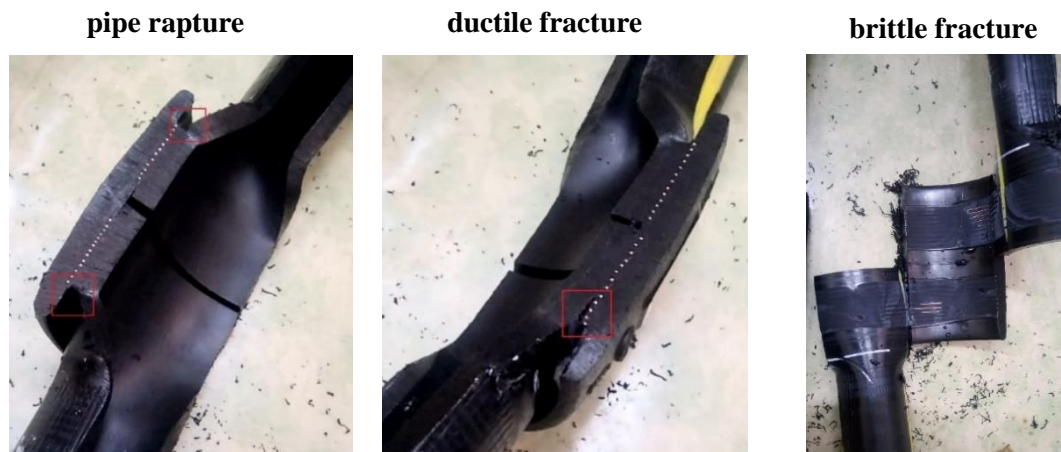
The fracture surface formed during crush test (brittle fracture, ductile fracture and pipe rapture)

Figure 12: the results of crush test

Among the tested samples, half suffered brittle fracture and half completed the test without fracture, which, overall, indicates that the welding quality is uncertain based on crush test.

Dur to the unsuccessful use of this cooling method in experiments, the rapid cooling cycle under similar conditions were simulated and the results are presented in figures (13), (14) an (15). Since cooling using ice and water mixture in experiments has been applied from both inside and outside the pipe, this mechanism was considered during simulations and using convection heat transfer equations, the heat transfer coefficient was calculated to be 6.0 W/m2K for inside the pipe and 6.6 W/m2K for outside.

Figure (15) shows that heat distribution rate inside and outside the coupling are almost identical and that temperature gradient has been suitably controlled. However, simply having a uniform heat distribution does not mean that the time for reaching this temperature for inside and outside are also similar.
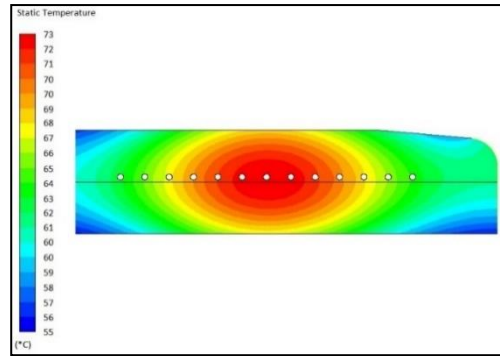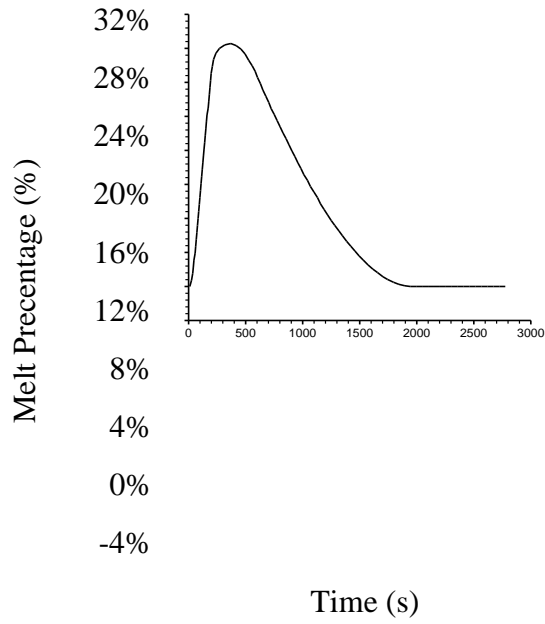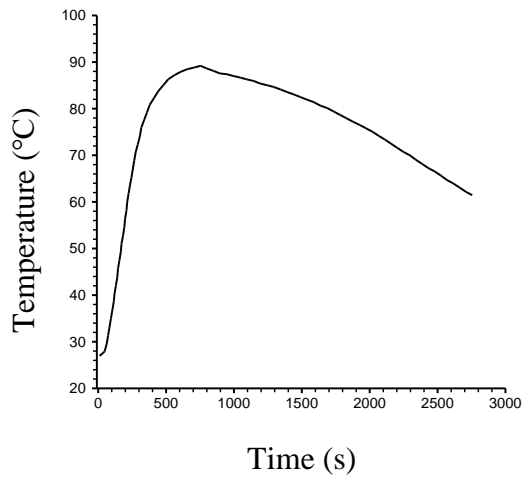
Figure 14: Changes in the molten polymer percentage after cooling with water and ice with conditions similar to the experimental studies

Figure 13: Temperature counter after cooling with water and ice mixture under experimental conditions ending at 2700 seconds
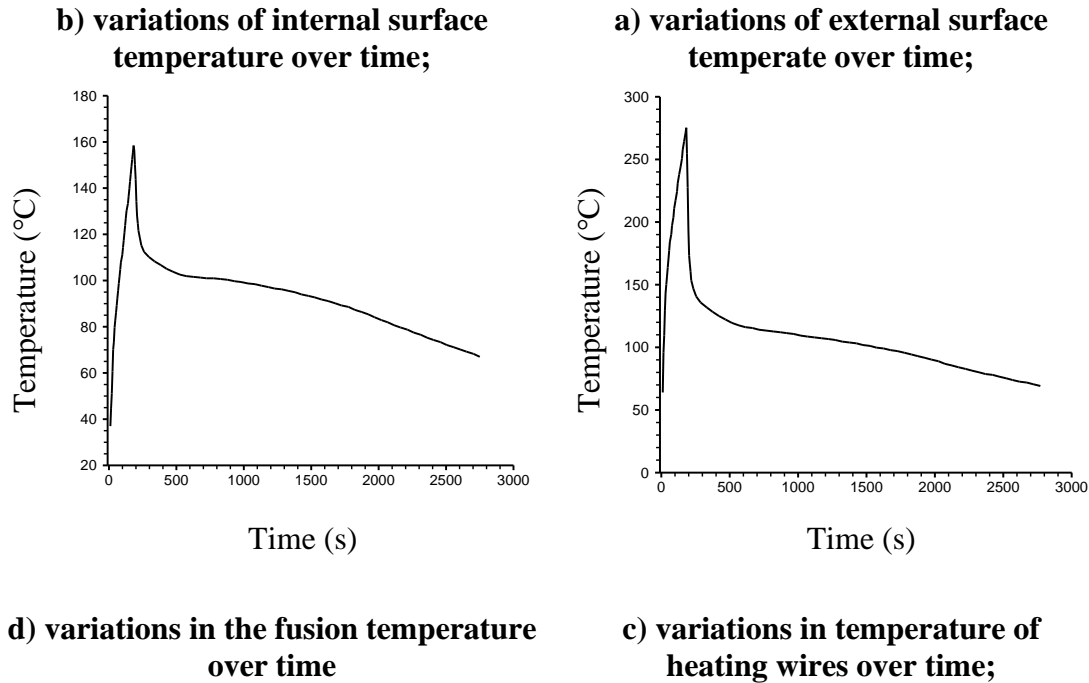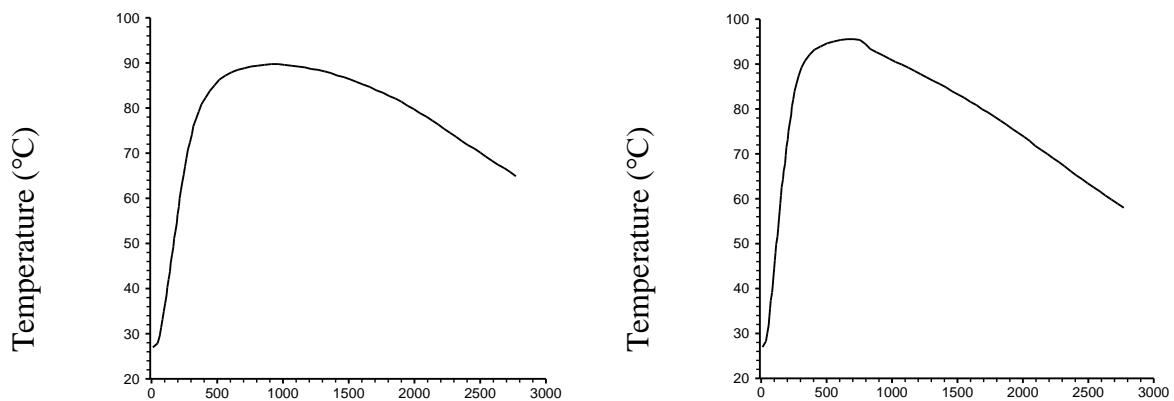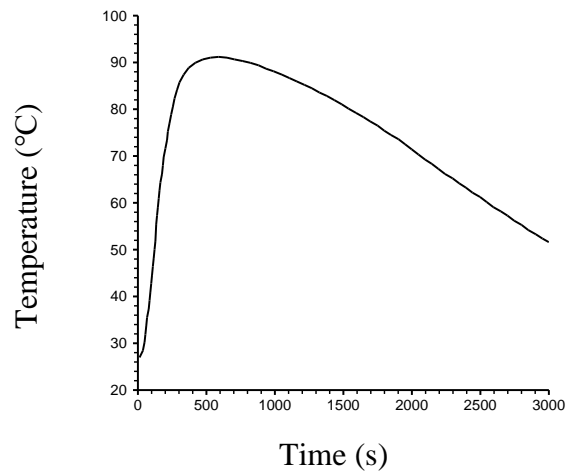
b) variations of internal surface temperature over time;

a) variations of external surface temperate over time;

d) variations in the fusion temperature over time

c) variations in temperature of heating wires over time;
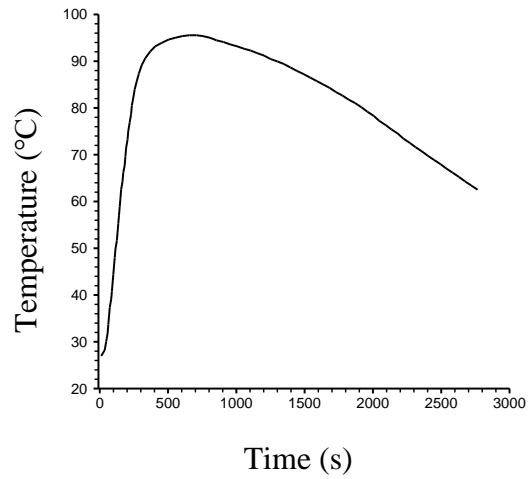
Figure 15: Changes in temperature over time for cooling with water and ice with conditions similar to the experimental studies

Dry Ice

It is assumed that the dry ice used in simulations is at the temperature of -50°C and convection heat transfer coefficient of 4.9 W/m2K [32].

Another assumption is that the pipe and coupling is placed in dry ice container, during which the fluid is stationary. Figures (16), (17) and (18) show the method in which rapid cooling is carried out after initial cooling under natural conditions (780 seconds after the start of electrofusion process) while figures (19), (20) and (21) show the method in which rapid cooling is applied immediately after the end of heating (180 seconds after the start of electrofusion). In both cases, the pipe is cooled using natural convection with coefficient of 6.4 W/m2K.

Time (s)

Time (s)

b) variations of internal surface temperature over time;

a) variations of external surface temperate over time;

Time (s)

Time (s)

d) variations in the fusion temperature over time

c) variations in temperature of heating wires over time;
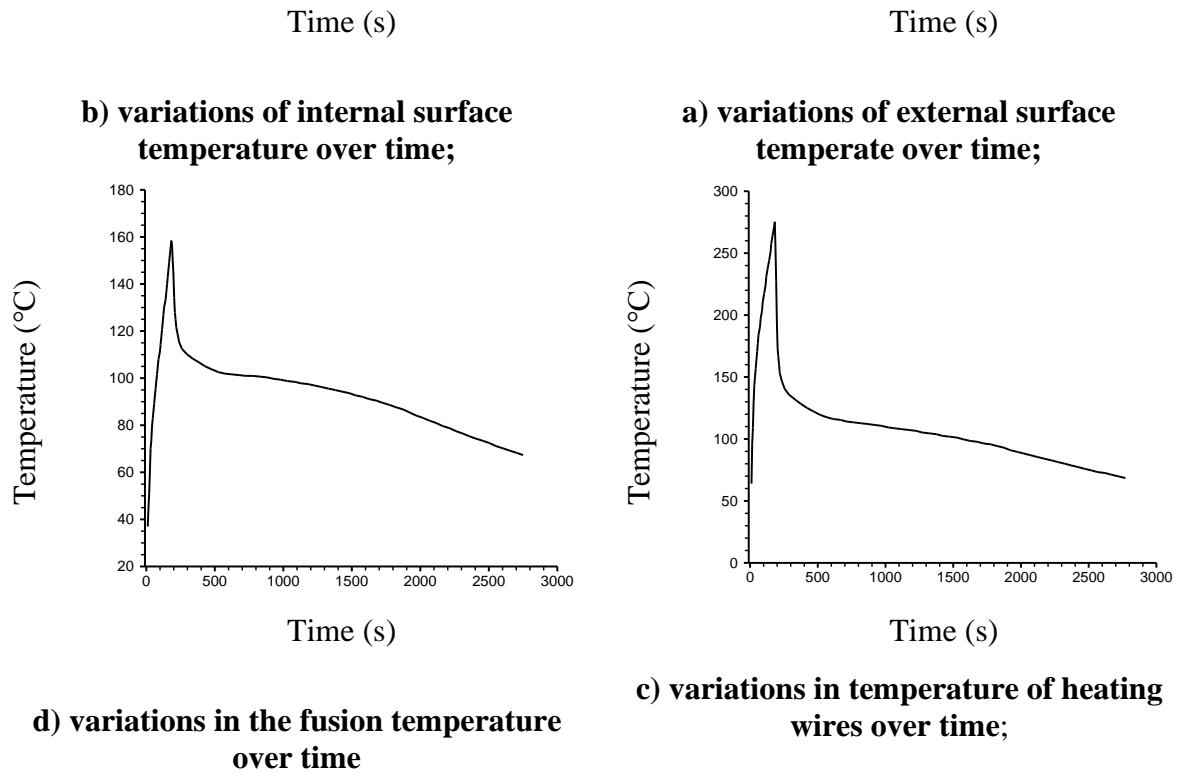
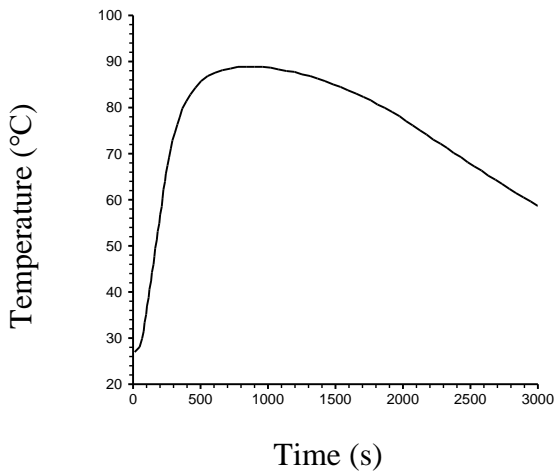**Figure 16: Changes in temperature over time for cooling with dry ice 780 seconds after the start of the electrofusion**
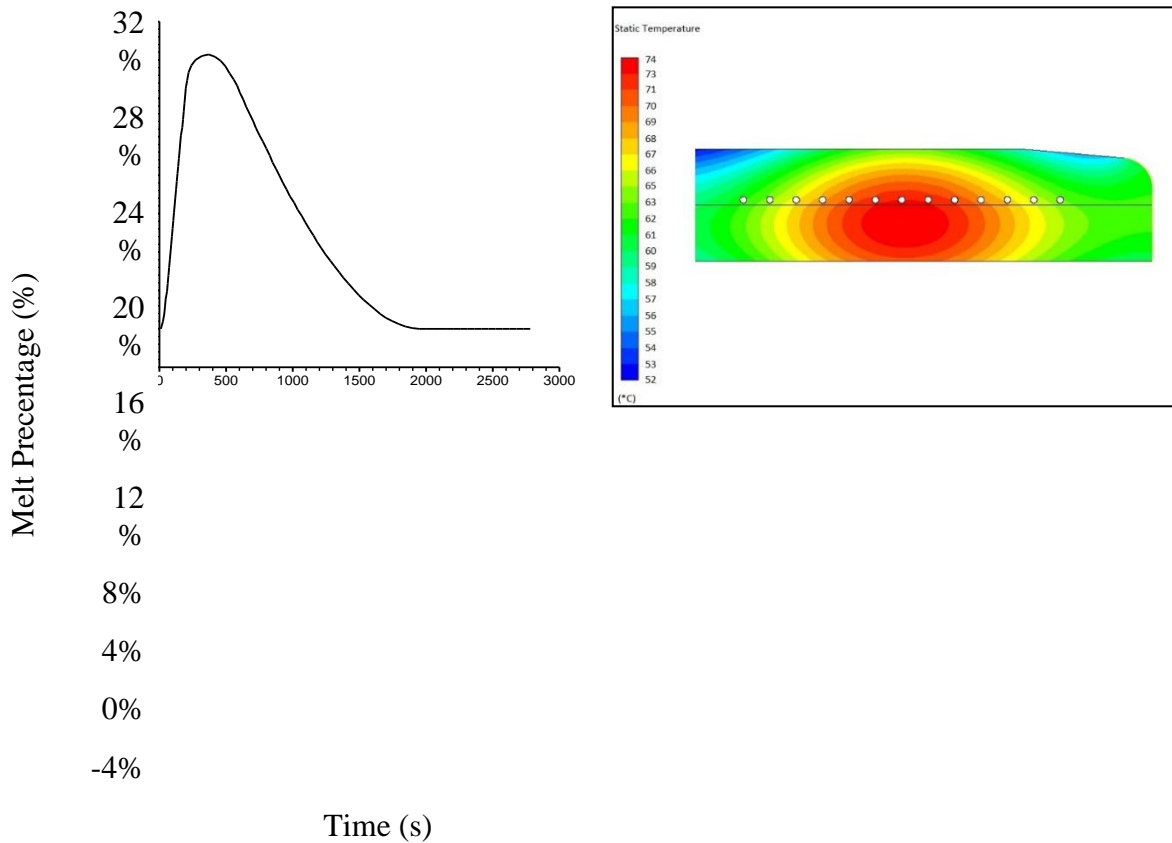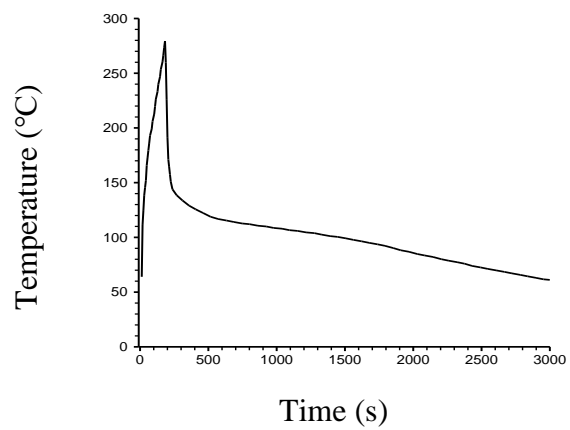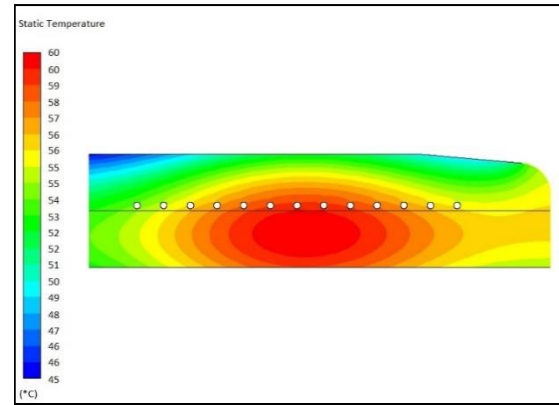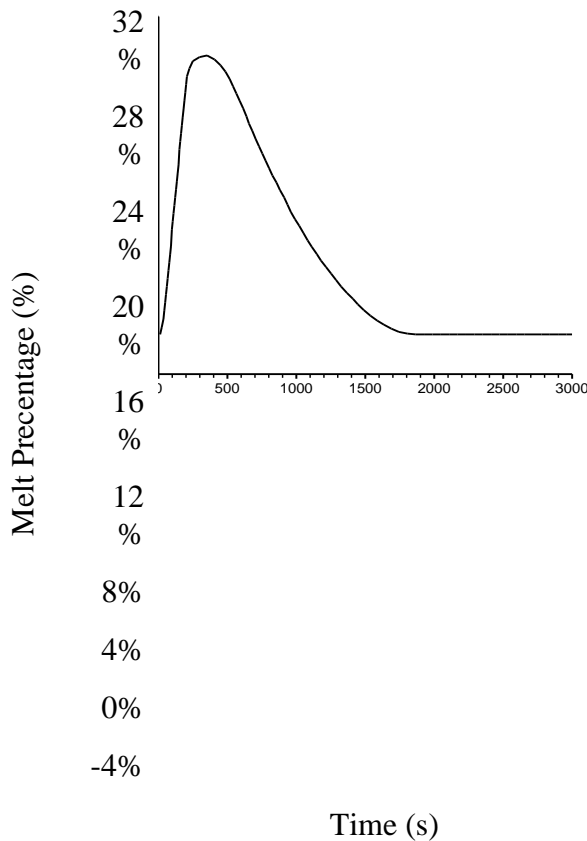
Figure 18: Changes in the molten polymer percentage after cooling with dry ice 780 seconds after the start of the electrofusion

Figure 17: Temperature counter after cooling with dry ice 780 seconds after the start of the electrofusion

b) variations of internal surface temperature over time;

a) variations of external surface temperate over time;
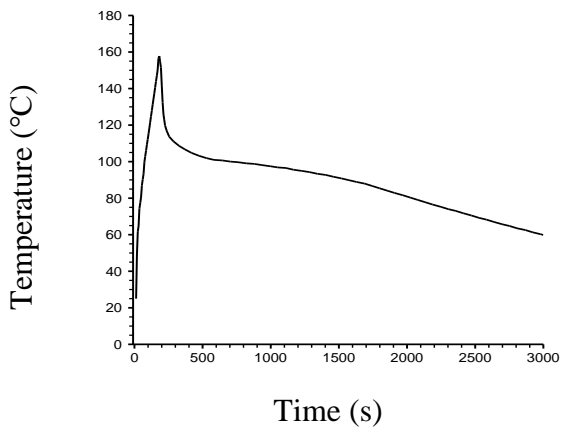
d) variations in the fusion temperature over time

c) variations in temperature of heating wires over time;

Figure 19: Changes in temperature over time for cooling with dry ice 180 seconds after the start of the electrofusion

Figure 21: Changes in the molten polymer percentage after cooling with dry ice 180 seconds after the start of the electrofusion

Figure 20: Temperature counter after cooling with dry ice 180 seconds after the start of the electrofusion

In cooling using the first method (figure 18), molten polymer volume reaches zero 1970 seconds after the start of the electrofusion process while in the second method (figure 20), zero volume is achieved after 1850 seconds. Since in the first method, part of the crystallization occurs during the natural cooling phase, the exothermic crystallization process reaches a somewhat steady state and results in uniform and decreasing heat dispersion after rapid cooling with dry ice.

Among the advantages of dry ice are its lower temperature and lower convection heat transfer coefficient. This results in larger changes in ΔT and therefore the resulting q". The graphs obtained for dry ice samples indicate that this method results in minimal changes compared to natural cooling during welding.

Water under natural conditions

During this analysis, water with temperature of 25°C and relative velocity of 0.1 m/s is used. Then, in one method, rapid cooling is carried out after the initial natural cooling (780 seconds after the start of electrofusion) using forced convection flow on the outside of the coupling and natural cooling inside the pipe with heat transfer coefficient of 6.4 W/m2K and the results are presented in figures (22), (23) and (24).
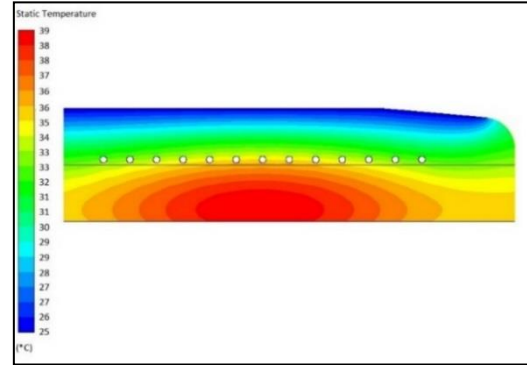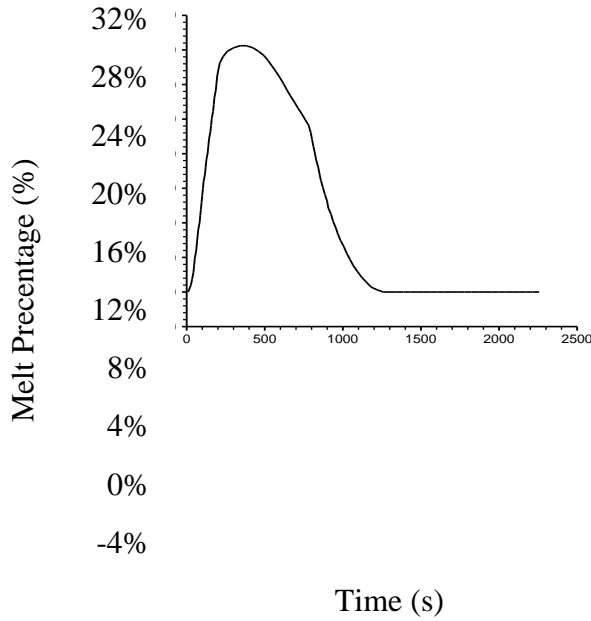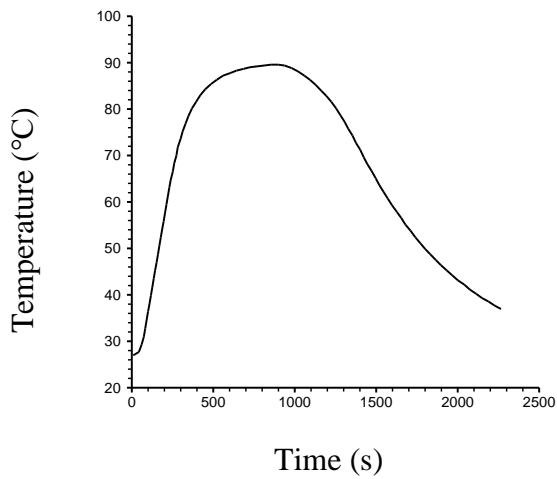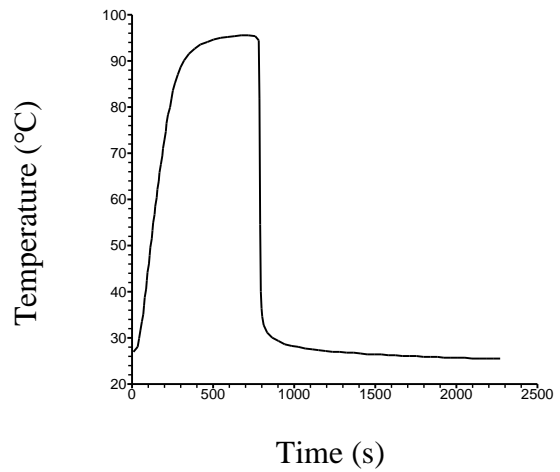
Figure 23: Changes in the molten polymer percentage after cooling with 25℃ water 780 seconds after the start of the electrofusion
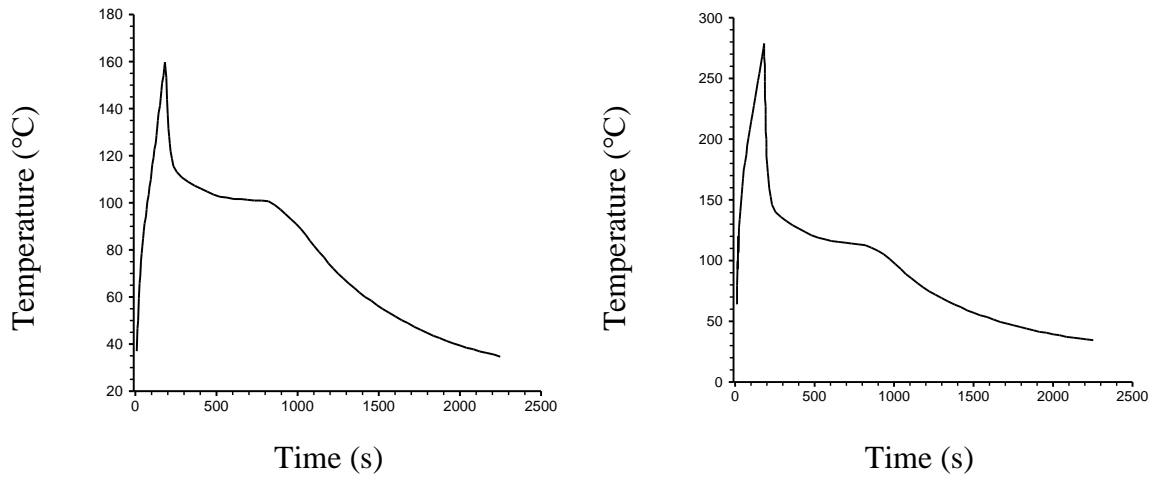

Figure 22: Temperature counter after cooling with 25℃ water, 780 seconds after the start of the electrofusion

b) variations of internal surface temperature over time;

a) variations of external surface temperate over time;
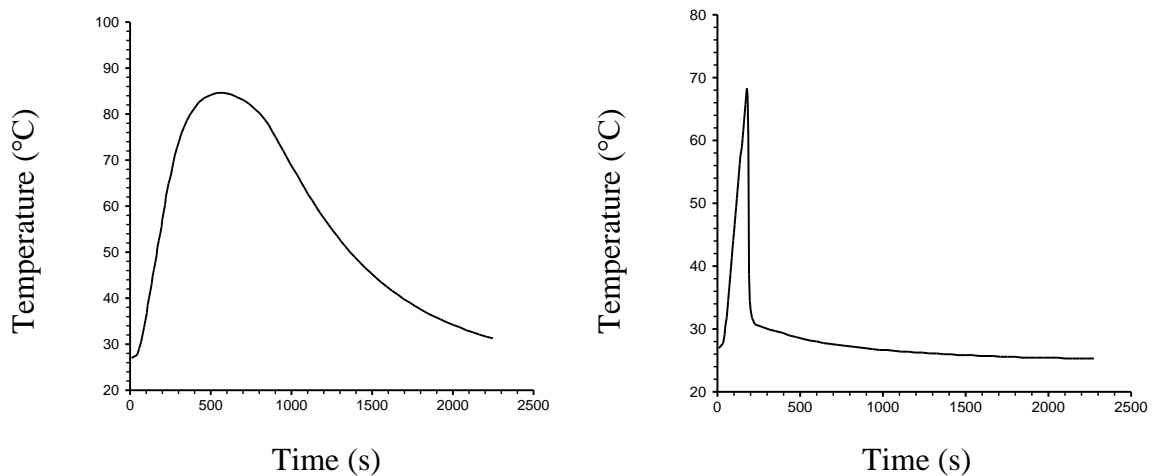
d) variations in the fusion temperature over time

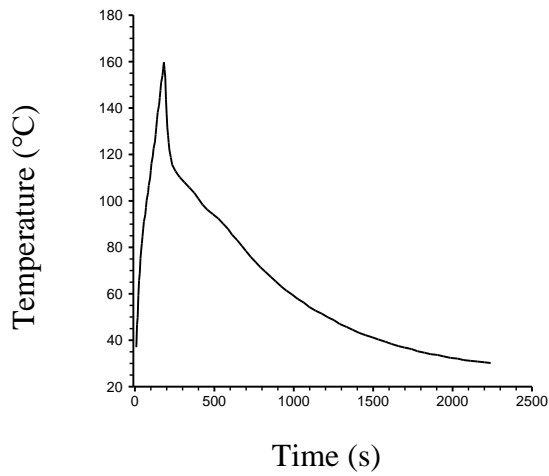**c) variations in temperature of heating wires over time;**

Figure 24: Changes in temperature over time for cooling with 25°C water 780 seconds after the start of the electrofusion

Figures (25), (26) and (27) show the results for rapid cooling using water immediately after the end of heating time (180 seconds after the start of electrofusion welding) using forced convection on the outside and natural flow in the inside of the pipe with heat transfer coefficient of 6.4 W/m2K. Under these conditions, molten polymer volume reaches zero 900 seconds after the start of welding process and only some temperature gradient exists at the center and internal surfaces which reaches the ambient temperature after 1000 seconds from the start of the process.

In cooling using the first method (780 seconds after the start of welding), since crystallization step is not finished, the results are similar to rapid cooling with ice and water mixture and will result in problems for the quality of the coupling. Therefore, this method is not recommended unless the rapid cooling is applied after the end of crystallization or if the cooling is carried out at a lower rate.
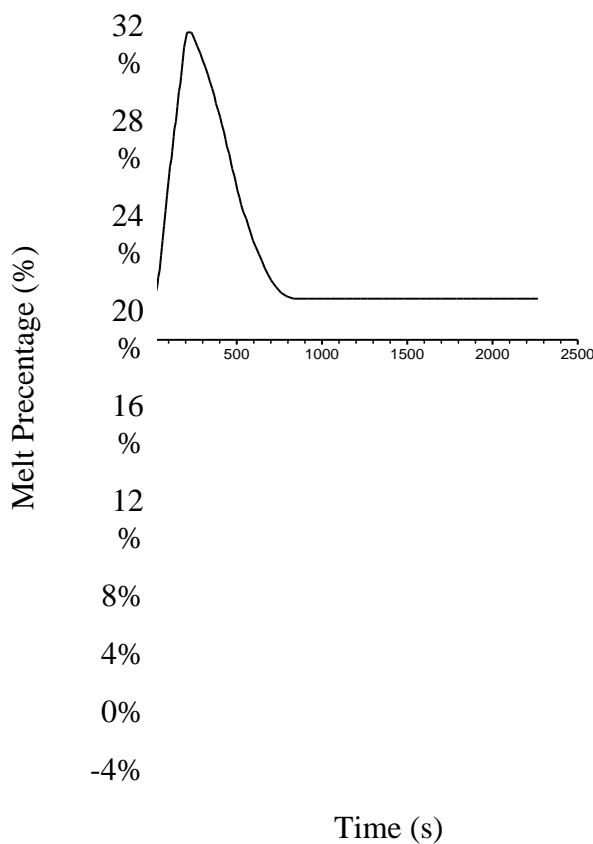
b) variations of internal surface temperature over time;

a) variations of external surface temperate over time;
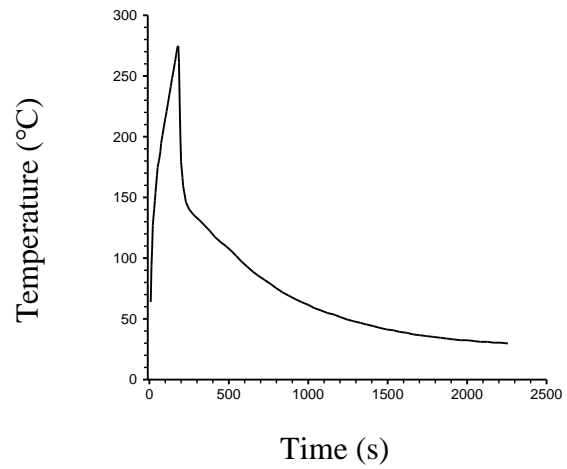
d) variations in the fusion temperature over time

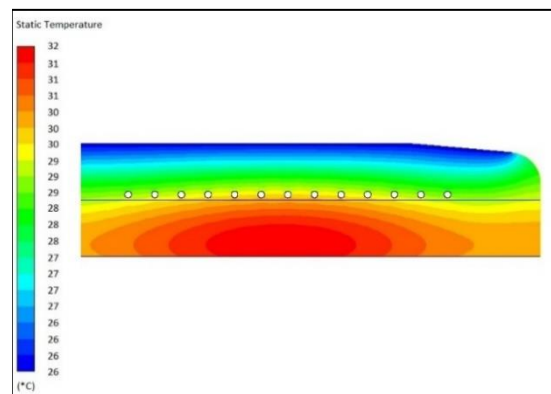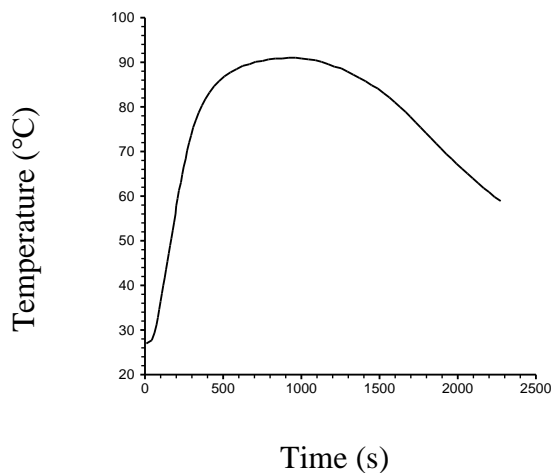**c) variations in temperature of heating wires over time;**

Figure 25: Changes in temperature over time for cooling with 25°C water 180 seconds after the start of the electrofusion

Figure 27: Changes in the molten polymer percentage after cooling with 25°C water 180 seconds after the start of the electrofusion

Figure 26: Temperature counter after cooling with 25°C water, 180 seconds after the start of the electrofusion

Air under natural conditions

In this analysis, air with temperature of 25°C and relative velocity of 10 m/s and forced convection coefficient of 41.3 W/m2K is selected. First, the simulation is carried out using forced convection flow on the outside and natural flow on the inside of the pipe with heat transfer coefficient of 6.4 W/m2K after the end of initial cooling (780 seconds after the start of welding). These results are presented in figures (28), (29) and (30). Then, simulation of rapid cooling immediately after heating phase (180 seconds after the start of welding process) is carried out, the results of which are presented in figures (31), (32) and (33).
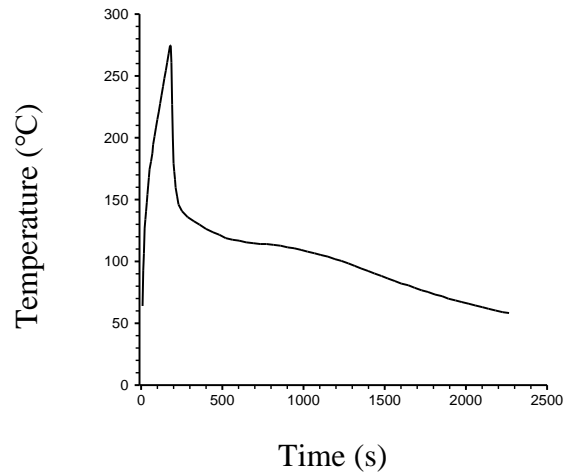
b) variations of internal surface temperature over time;
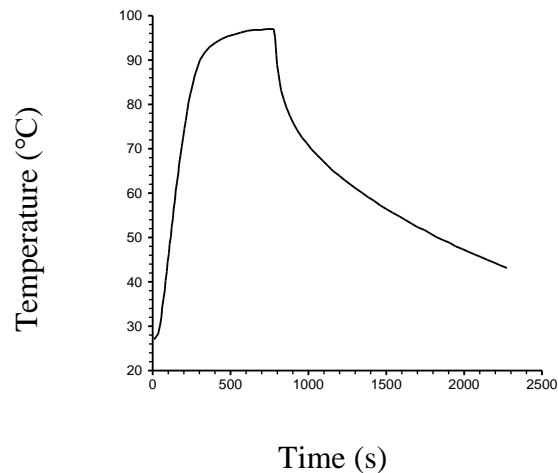
a) variations of external surface temperate over time;
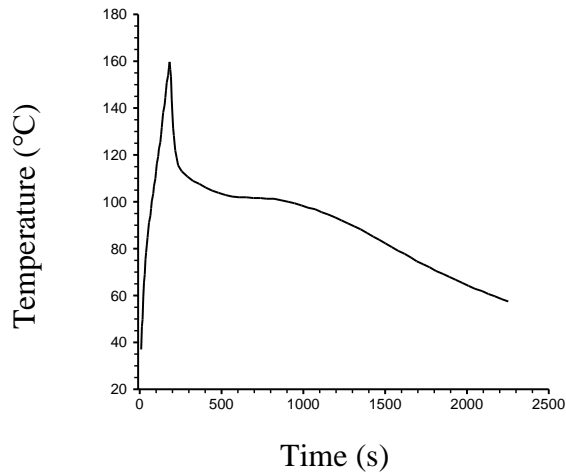
d) variations in the fusion temperature over time

c) variations in temperature of heating wires over time;

Figure 28: Changes in temperature over time for cooling with air at relative velocity of 10 m/s, 780 seconds after the start of the electrofusion

Figure 30: Changes in the molten polymer percentage after cooling with air at relative velocity of 10 m/s, 780 seconds after the start of the electrofusion

Figure 29: Temperature counter after cooling with air at relative velocity of 10 m/s, 780 seconds after the start of the electrofusion

b) variations of internal surface
temperature over time;

a) variations of external surface
temperate over time;

d) variations in the fusion
temperature over time

c) variations in temperature of heating
wires over time;

Figure 31: Changes in temperature over time for cooling with air at relative
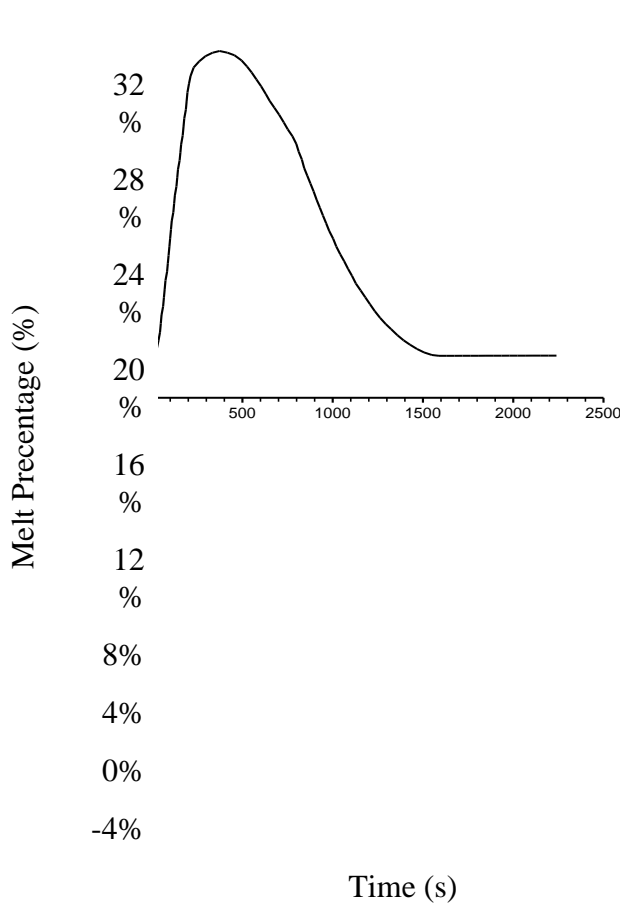velocity of 10 m/s, 180 seconds after the start of the electrofusion

Figure 33: Changes in the molten polymer percentage after cooling with air at relative velocity of 10 m/s, 180 seconds after the start of the electrofusion
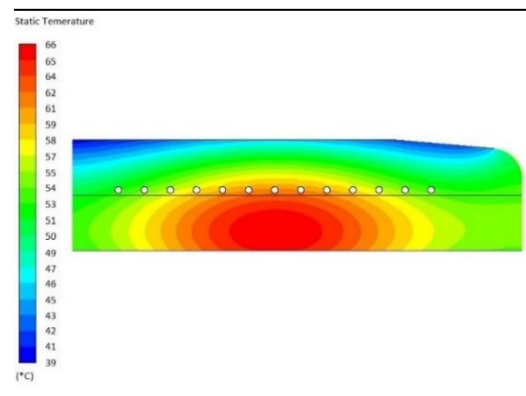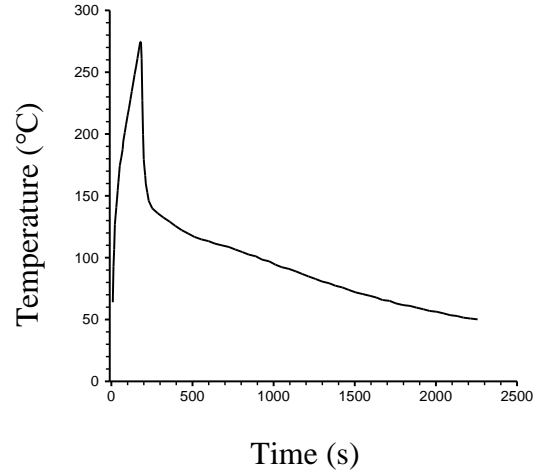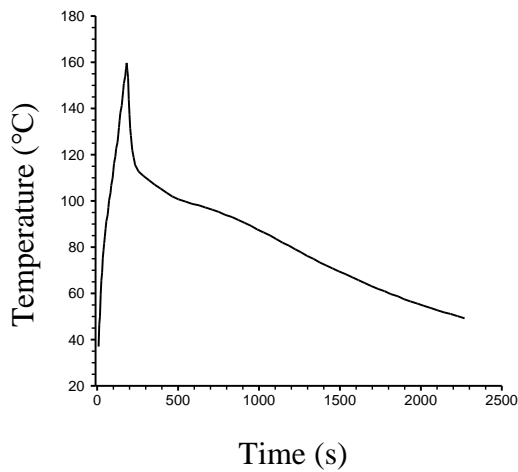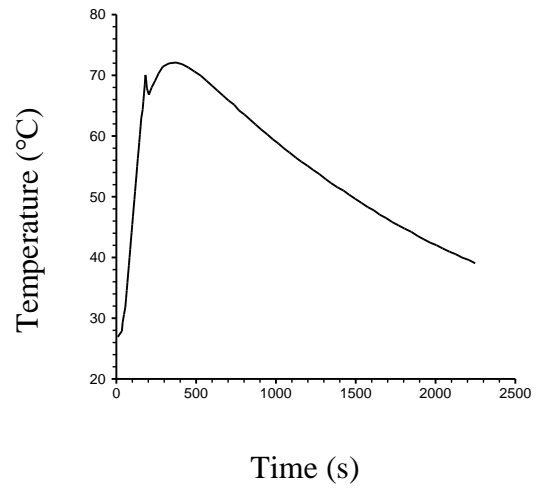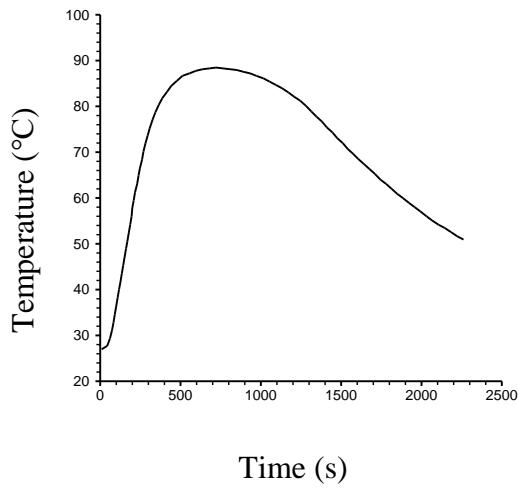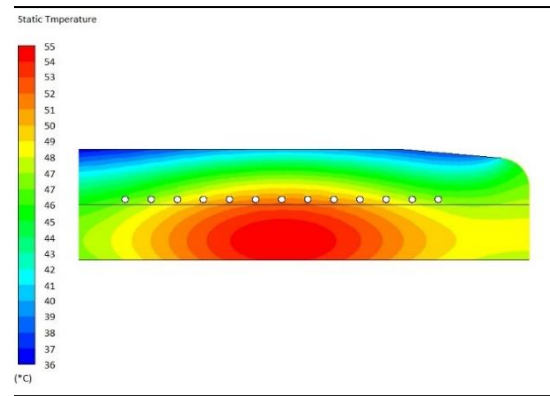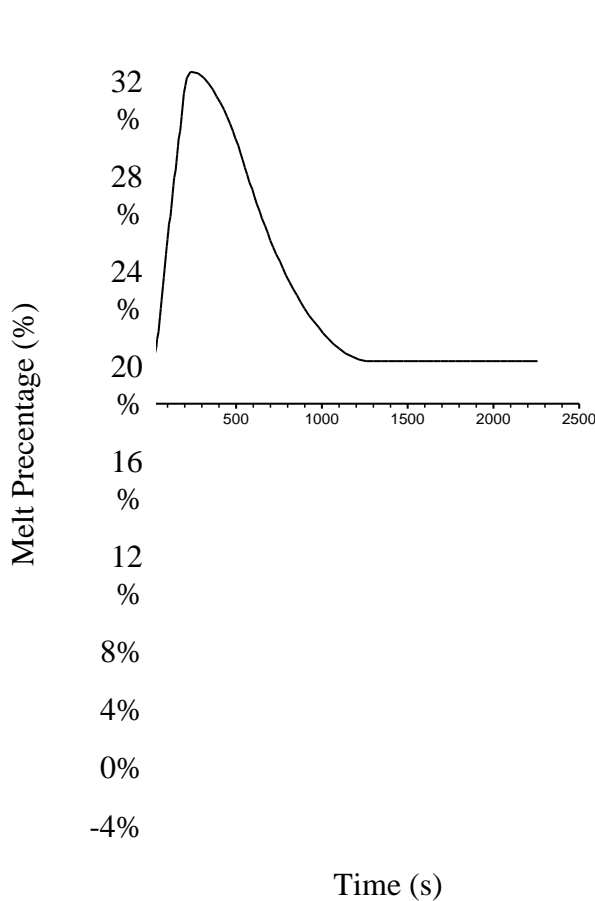

Figure 32: Temperature counter after cooling with air at relative velocity of 10 m/s, 180 seconds after the start of the electrofusion

During the initial analysis of cooling using air, in the first approach and according to figure (29), molten polymer volume reaches zero at 1590 seconds after the start of the process while this method is equal to 1260 seconds for the second approach. These show 23% and 40% decrease in overall welding time compared to the natural cooling method, respectively.

In the second cooling approach and as shown in figure (33), after around 40 seconds from the start of cooling process and reaching the surface temperature of 67°C, the exothermic crystallization process has been dominant compared to the convection heat transfer and has resulted in a heating pulse due to its exothermic nature, increasing the surface temperature to 72°C.

Figure (34-a) shows temperature variations in cases where rapid cooling with various fluids is carried out after the initial cooling period. According to these results, although water cools the coupling during a shorter period of time, it also results in various welding quality problems. On the other hand, use of air flow and dry ice can help reduce these negative effects.

Figure (34-b) also shows that temperature variation during rapid cooling with air and dry ice have a more uniform slope and don't result in sudden freezing of the molten polymer. This allows the crystals to gather

around the initial nuclei and increases the crystallinity compared to cooling with water and ice and water mixture.

b) cooling immediately after heating   a) cooling after the initial cooling period;
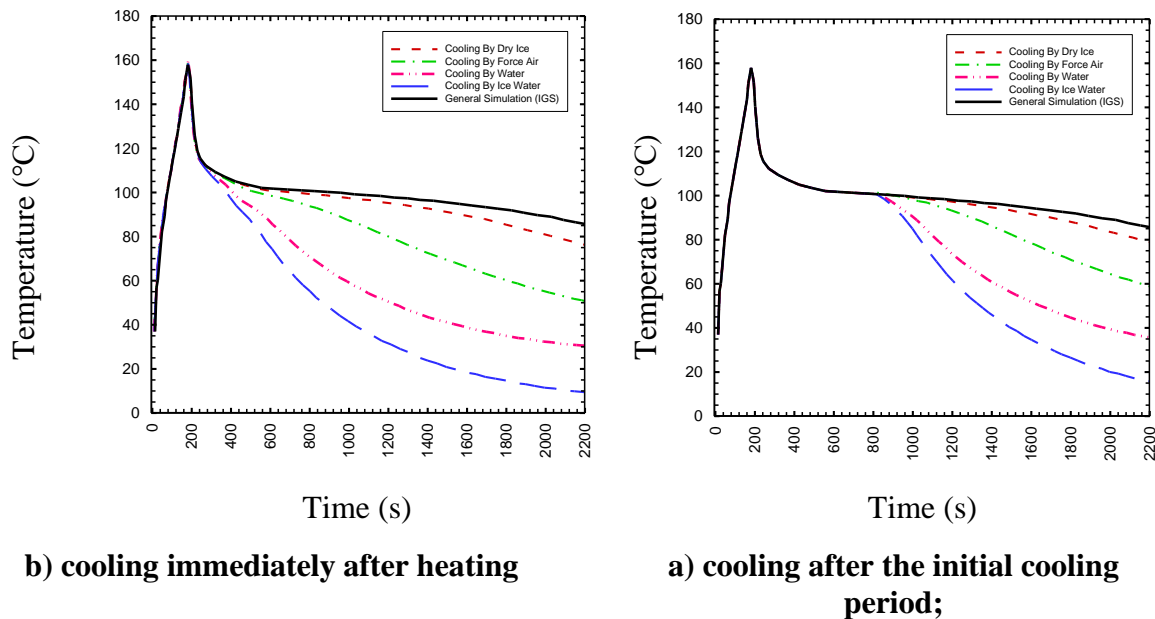
Figure 34: comparison of variations in temperature of fusion surface over time for different cooling fluids

analyses of various samples used for rapid cooling show that it is better for the rapid cooling to start after the end of the crystallization step or to use fluids such as air or dry ice to finish the initial cooling with a suitable rate before rapidly cooling the surface with another fluid such as water after the end of crystallization step.

Suggested methods for rapid cooling

Due to naturally high convection heat transfer in water, it is optimal to use water with the smallest possible temperature difference with the surface while in air, since convention heat transfer is relatively small, the temperature must be optimized as low temperatures will result in physical problems in the welding compared to the reference values and too high temperatures will not provide the necessary reduction in the cooling time. Therefore, rapid cooling with water at 30°C and relative velocity of 0.5 m/s and air with temperature of 25°C and relative velocity of 100 m/s are investigated under two conditions. Figure (35) shows the results for cooling from both inside and outside and the results of cooling only from outside of the pipe for water and air.

b) cooling with water   a) cooling with air;
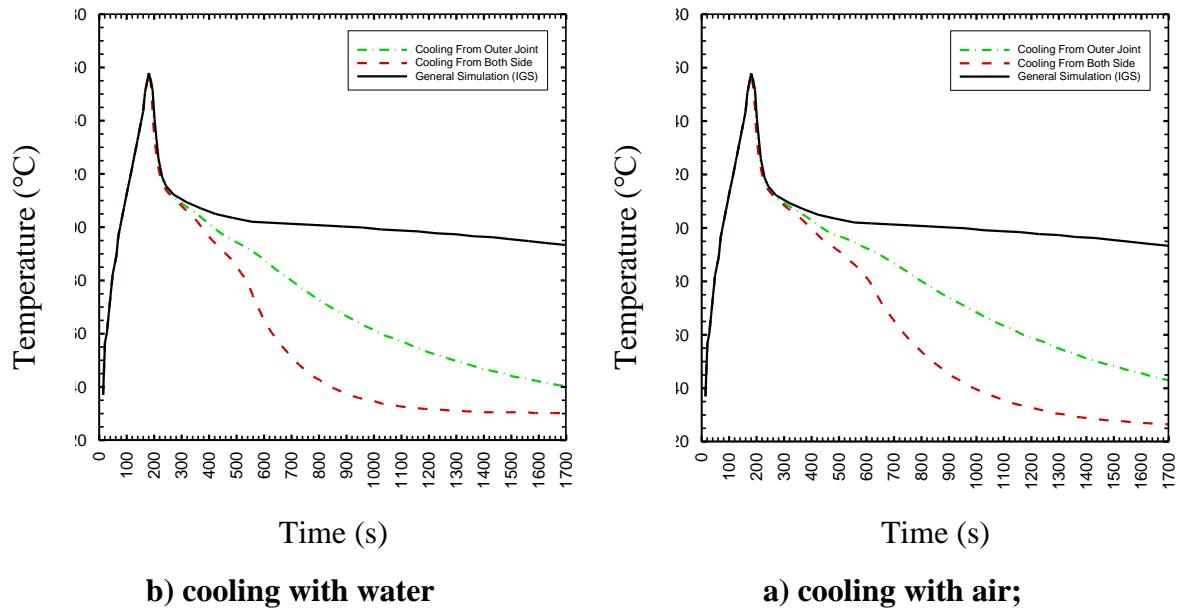
Figure 35: Comparison of changes in fusion surface during cooling from both inside and outside and cooling from only outside of the pipe for

Table (2) shows the variations of crystallization percentage and strength along with density changes at a reference temperature and at the end of crystallization for cooling with air with temperature of 25°C and relative velocity of 100 m/s and water at 30°C and relative velocity of 0.5 m/s.

Table 2: changes in strength and crystallinity compared to natural cooling for water and air fluids with proposed conditions

Cooling By	Cooling From	Time & Velocity	At the end of crystallization	Density at reference temperature	Precent changes in strength and crystallinity compared to natural conditions
Air	Outer Joint	T=25 (°C) & V= 100	943 Second	878.206 (Kg/m^3)	0.712%
Air	Both Side	T=25 (°C) & V= 100	637 Second	873.803(Kg/m^3)	1.209%
Water	Outer Joint	T=30 (°C) & V= 0.5	835 Second	877.867 (Kg/m^3)	0.750%
Water	Both Side	T=30 (°C) & V= 0.5	553 Second	873.444 (Kg/m^3)	1.250%
Natural Convection			2060 Second	884.50 (Kg/m^3)	-

It can be assumed that smallest changes occur when there are no more than 0.5 to 1% change in physical characteristics compared to the natural state. On the other hand, a more optimal condition is when we reach zero molten polymer volume at the shortest possible time while minimizing the percentage of changes in physical properties. Figure (36) shows changes in crystallinity percentage versus the time for reaching zero molten polymer volume.
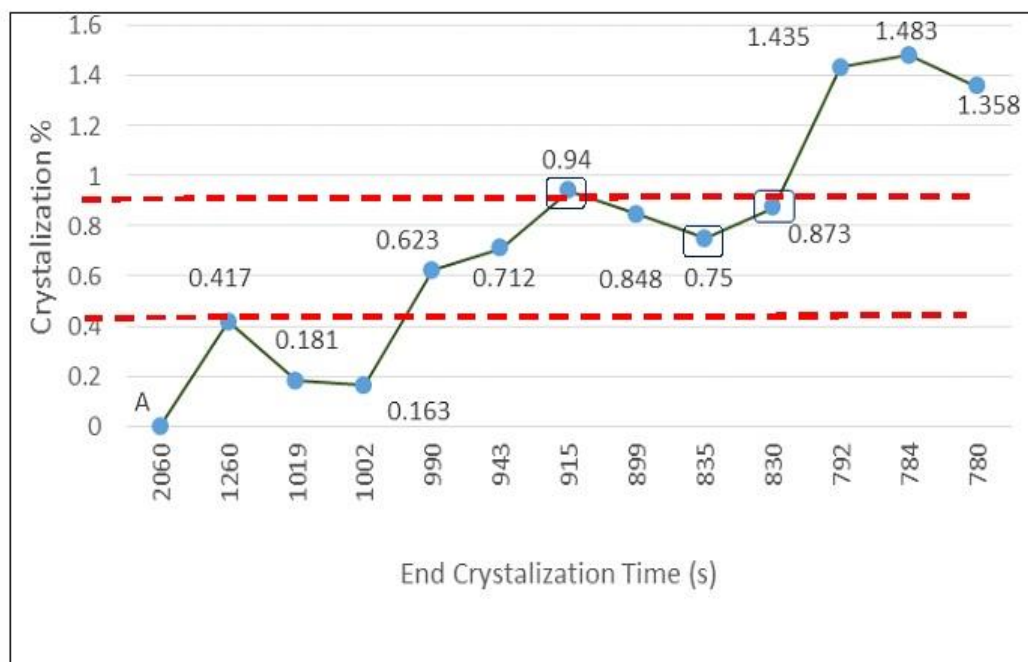

Figure 36: Comparison of crystallinity versus time for reaching zero molten polymer volume for cooling with water and air

These results indicate that in order to achieve the shortest cooling time with 0.5 to 1% change in crystallinity, it is suitable to use water with temperature of 30°C and velocity of 0.5 m/s, air with temperature of 20°C and velocity of 100 m/s or water at temperature of 25°C and velocity of 0.1 m/s. This shows the advantages of water over air based on the investigated parameters.

Finally, despite better results of water cooling, using air cooling is recommended due to factors such as better control, better operational conditions, easier velocity control, simpler flow adjustment and the possibility of creating air flow in both inside and outside of the pipe.

CONCLUSION
1. The least amount of changes during rapid cooling compared to the natural method occurred for the highest temperature difference between fluid and surface and lowest convection heat transfer coefficient or smallest difference in temperature with higher convection heat transfer coefficient.

2. Since water as a cooling fluid has a high convection heat transfer coefficient, it is best to use the fluid with the smallest possible temperature difference with the surface while in water, due to its low convection heat transfer coefficient, selected temperature of the fluid must not be too low to prevent decrease in physical properties compared to the reference samples while also satisfying the decrease in cooling time as a result of rapid cooling. Therefore, water with temperature of 30°C and velocity of 0.5 m/s and air with temperature of 25°C and velocity of 100 m/s were investigated using two different conditions.

3. Cooling from outside the coupling is effective only when heat transfer rate from the coupling's surface toward the inside of the pipe is small and uniform. This is due to the fact that sudden decrease in the temperature of outside surface cannot result in uniform changes in internal surface. This then leads to nonuniformity of crystalline structures and failure of the welding in quality assurance tests.

4. Simultaneous cooling from both inside and outside of the coupling is effective in controlling the temperature gradient and uniform decrease of the temperature. However, this method is not feasible for practical applications. This method also cannot be used to suddenly decrease the temperature, since high cooling rates will also lead to low welding quality.

5. Since there are no suitable criteria for changes in crystallinity percentage which can be used to determine the amount of deviation from natural state which will lead to unsuitable crush test results, current data cannot be used to determine a suitable crystallinity percentage.

6. Within the range of 0.5 to 1% change in crystallinity percentage compared to the natural state, lowest cooling times can be achieved using water with temperature of 30°C and velocity of 0.5 m/s, air with temperature of 20°C and velocity of 100 m/s or water at temperature of 25°C and velocity of 0.1 m/s, respectively. This shows the advantage of water over air based on the investigated parameters.

7. Within the range of 0.5 to 1% change in crystallinity percentage compared to the natural state, largest changes are seen when using air as cooling fluid. This shows the advantage of air when it comes to flexibility of the operation. According to the existing values for this range, 4 results have used air and 2 have use water. However, decrease in cooling time in the 2 cases using water is higher than the cases using air.

8. Use of air can be considered due to higher flexibility, better operability, easier velocity control, easier temperature adjustments in the air flow and relatively simply setup for achieving air flow both inside and outside of the pipe. However, using water results in a smaller cooling time compared to air. Finally, the most important criteria for selection of cooling fluid should be determined through operational tests along with quality control tests of the resulting weld.

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